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Peaceful Nuclear Explosions

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Such a cavity was formed during the Gnome explosion, carried out by American specialists on December 10, 1961.

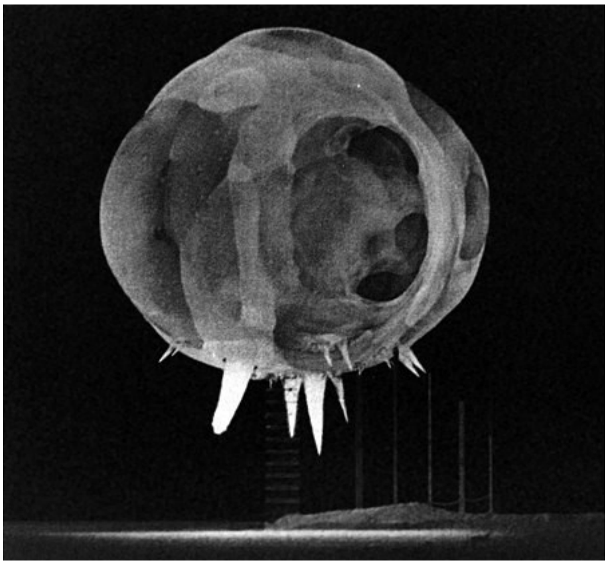
Peaceful nuclear explosions are explosions for non-military purposes carried out using nuclear charges, for example to destroy high-level waste [1] . The production of such explosions is limited by various international treaties [2] . It is believed that any technology used in peaceful nuclear explosions can be replaced by a non-nuclear alternative, and many nuclear explosions carried out for peaceful purposes have caused disasters [3] . Peaceful nuclear explosion programs were actively funded in the Soviet Union and the United States of America . The first underground nuclear explosions took place in the late 1950s - early 1960s [4] : p. 11 .

In the United States, a series of tests were conducted under the Plowshare program , established in 1957 [5] . The largest underground test, Sedan , was conducted by the Americans in 1962 , when a large amount of radioactive gas was released into the air. Public resistance to the experiments became apparent in the late 1960s; in the 1970s, the economic concept of the program was questioned by researchers [6] . In 1977, the project was deprived of funding; in total, American specialists conducted 27 explosions during the program [7] : p. 5 .

The implementation of the Soviet Program No. 7 "Nuclear Explosions for the National Economy" began in 1965 [8] [9] . In total, scientists managed to conduct 124 nuclear tests [5] . A number of experiments were accompanied by emissions of radioactive substances. A large place in the program was occupied by work to eliminate gas fountains [10] . In 1988, the program was officially closed [4] : pp. 183-184 . Statements about the successful use of nuclear explosions by Soviet specialists to extinguish fires at gas wells were subsequently widely mentioned in the development by the Americans of technologies that would have stopped the oil spill on the Deepwater Horizon platform in the Gulf of Mexico , which occurred in 2010 [11] [12] .

Plowshare (USA)

While developing the world's first atomic bomb, scientists at the Los Alamos National Laboratory in the United States studied the possibilities of using the energy of a nuclear explosion for peaceful purposes. First and foremost, this was the use of thermal energy generated by the slow fission of uranium in nuclear reactors [7] : p. 2. Although the researchers focused primarily on military applications, they also considered other uses for atomic bombs . Thus, physicist Otto Frisch , a pioneer in the field of nuclear fission, put forward the idea of directing atomic explosions to release a large number of neutrons : such potential could be used for scientific experiments in the field of nuclear physics [7] . The mathematician John von Neumann proposed using nuclear charges for



A photograph taken at the moment of the explosion under the American Tumblr-Snapper program (1952). Bright peaks stretch beneath the fireball - they owe their appearance to a flash of radiation that heated the guy wires to white heat.

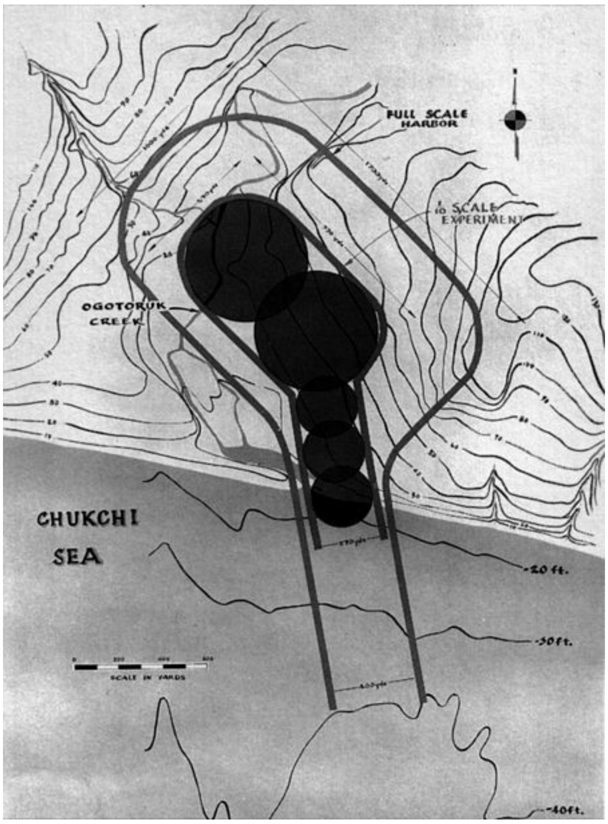
Analysis of the fallout from the US Ivy Mike test revealed the chemical element einsteinium (1952).

In June 1950, American Frederick Reines , who had joined the Lawrence Radiation Laboratory team in 1944 , published a critical article in the Bulletin of the Atomic Scientists in which he outlined the prospects for using nuclear explosions in scientific research and large-scale transformations of the earth's crust, in particular in the construction of canals, mining , and breaking up ice, but he doubted their practical feasibility: the scientist recalled that nuclear explosions are associated with the risk of radioactive radiation [14] . New opportunities were presented by the invention of thermonuclear explosive devices. Thermonuclear explosive devices were cheaper, used common hydrogen isotopes , produced fewer fission products, and had an unlimited power reserve; soil development could now be done cheaper than using traditional methods. These devices used a small trigger to initiate fission, and relatively inexpensive deuterium and lithium were used as fuel ; in addition, such designs produced fewer long-lived radioactive products [7] .

The world's first thermonuclear explosion occurred in 1952 at Enewetak Atoll in the Pacific Ocean [15] . Its yield was 10 megatons, and it created a large crater in the reef. In the wake of the Suez Crisis that broke out in 1956 , the head of the Laboratory, Harold Brown, considered the option of using nuclear explosive devices to lay a canal through Israel . In February 1957, a special group was organized at the Laboratory to study the possibility of such applications. And in the summer of 1957, by decision of the American Atomic Energy Commission, the Plowshare program was formally adopted [13] : pp. 22-23 , the purpose of which was to study the possibilities of using nuclear explosions for industrial and scientific purposes. Soon after, the Commission began conducting underground nuclear tests. Already in the fall of 1957, the Rainier experiment was conducted at the Nevada Test Site. By detonating a charge located at a depth of 274 meters underground, American

scientists carried out an explosion with a power of 1.7 kilotons [7] : p. 3 [16] . As a result of the explosion, a shaft of cracked rock was formed, thanks to which information appeared about the potential use of nuclear charges in mining [13] : p. 24 .

Project "Gnome"



When developing the Chariot project, the Americans were planning to build an artificial harbor. The outer contour on the map was supposed to be covered by a powerful explosion of 2.4 megatons, the inner one - 460 kilotons.

The first field experiment of the program was Project Gnome [7] . In 1959, preparatory work was carried out, during which scientists conducted a series of tests using land mines and developed appropriate safety measures. Independent scientific recommendations on geophysics , seismology, and hydrology were prepared by a special group, which was approved by the US National Academy of Sciences . Having studied technical reports provided by the US Geological Survey and the Lawrence Livermore Laboratory, experts brought in by the Academy considered that Project Gnome would not affect the local population, existing and proposed deposits , or agricultural lands, and would not allow groundwater contamination [17] : p. 140 .

In accordance with the technical requirements set by the Laboratory, plans for engineering and construction work were developed; this was entrusted to the American firm Holmes and Narver [17] : p. 139. Several companies took on the construction work; they had to dig a 336-meter shaft and a 340-meter tunnel that would lead from the bottom of the shaft to the site of the explosion itself. General support and minor construction assignments were provided by contractors and employees of the Reynolds Company sent from New Mexico. The specialists were looking for a relatively clean salt layer with a low water content, located no more than 244 meters below the surface, and in a sparsely populated area, preferably on government lands related to the continental part of the United States of America [13] : pp. 27-28 . The 1961 3.1-kiloton explosion followed the expiration of the nuclear moratorium and took place in a salt formation near the city of Carlsbad in southeastern New Mexico [7] .

As a result, a cavity with a volume of about 27,000 cubic meters was formed, and about 2,400 tons of rock melted. The molten rock mixed with 13,000 tons of salt rock, which was carried into the cavity during the implosion . The pressure of the water vapor accumulated in the rock blew blocks of rock off the walls of the cavity. The explosion led to the collapse of 15,000 tons of rock, forming an adit with a diameter of 41–60 meters and a height of 23 meters. The bulk of the non-gaseous radioactive products was trapped in the molten salt mixture and the buried debris [13] . The explosive device used in Project Gnome was assembled by scientists sent by the Lawrence

By September 1961, the Vela Uniform program, carried out by the Defense Advanced Research Projects Agency of the United States Department of Defense, had joined as escorts [13]: p. 28. Among the scientific tasks, the researchers considered the possibility of obtaining transplutonium isotopes that were formed at the time of the nuclear explosion. Experts believed that most of the non-gaseous isotopes would be concentrated in impurities contained in the salt and would retain these impurities when the materials dissolved. In addition, the American researchers intended to study the possibility of collecting the heat accumulated in the salt at the time of the explosion: for this purpose, water was pumped into the hot cavity and the parameters of the incoming steam were measured [17]: p. 142. As a result, the molten salt quickly cooled due to the influx of 13,000 tons of colder rock, which began to dissipate the heat - this made its extraction practically impractical. The resulting steam was characterized by high corrosive activity , which is why its use did not meet economic considerations [13]: pp. 29-30 .

The neutrons released during the nuclear reaction passed through a moderator and a 305-meter pipe, after which they fell on samples mounted on rotating disks. Neutrons with different energy levels struck the disks at different times. The work of retrieving the disks with neutrons was delayed, so some of the materials were lost [13]: pp. 30-31 . Due to the proximity of the site to the geological boundary between the Rocky Mountains and the Great Plains , Project Gnome assumed an extensive study using seismic instruments [17] . Thus, specialists found that variations in the timing of seismic waves indicate discrepancies in the Earth's upper mantle , and not the thickness of the Earth's crust [13] .

The Hardhat and Danny Boy Experiments

The US Department of Defense systematically conducted experiments with nuclear weapons in an effort to gain valuable information for the Plowshare program. For example, on February 15, 1962, at the Nevada Test Site, during the Hardhat experiment, American specialists detonated a 4.5-kiloton explosive device located 290 meters underground [13]: p. 35 [18] . The test was conducted in granite rock , typical of many mining operations; as a result, a cavity with a diameter of about 38 meters was formed [13] . A low-yield nuclear explosion, Danny Boy, took place at the Nevada Test Site on March 5, 1962, and led to the formation of a crater in basalt . The objective of this experiment was to determine the characteristics of craters formed in a hard, dry, inert medium, such as basalt, and to determine the radioactivity released during an explosion in hard rock [13] . The 420-ton explosion, which thundered at a depth of 34 meters underground, formed a crater 65 meters in diameter and 19 meters high [19]: p. 62. A base wave 884 meters in diameter and 305 meters high arose; 30 minutes after the explosion, the dust cloud reached a height of 610 meters. Only about 4% of the radioactive particles fell as precipitation, mainly settling within a radius of 3.2 kilometers from the explosion site. The experiment made it possible to obtain information on the change in shock wave pressure depending on the distance and on the seismic impact at different distances [13]: pp. 35–36 .

Project "Sedan"

On July 6, 1962, American scientists conducted another nuclear experiment, the Sedan explosion

explosion. It thundered at a depth of 194 meters, leaving behind a crater 366 meters in diameter and 98 meters high, its total volume being about 5,000,000 cubic meters [13] : p. 34 .

A crater 100 meters deep and about 390 meters in diameter, produced during the US nuclear test "Sedan".

The project was designed to develop nuclear excavation techniques and to study the damaging effects of larger crater-forming explosions [6] . Previous tests had been limited to one-kiloton blasts, and the predictive power of the data obtained from such tests for larger blasts was therefore unconvincing. Project Sedan also sought to collect data on radiation safety, seismic effects, and airbursts. After studying the fallout patterns, the researchers found that most of the radioactive particles released from the crater had settled in the immediate vicinity. The data obtained during the experiment confirmed the conclusion that the blast wave near the object was reduced to one-fifth to one-tenth that caused by a surface explosion of the same power. Measurements at ground stations indicated that the zone of dangerous seismic impact extended over a distance of about four kilometers [13] · 34 .

Other experiments

In 1964, the Handcar experiment was conducted at the Nevada Test Site, which involved a 12-kiloton explosion in a dolomite formation; it demonstrated the possibility of complete containment of the explosion gases in carbonate rocks. In order to develop methods for understanding the propagation of energy in non-spherical geometries, in 1967 American specialists conducted the Marvel test [4] : pp. 65–66 . The experiment allowed them to study the propagation of a shock wave near the explosion site, generated in a horizontal tunnel 1 meter in diameter and 122 meters long [7] : p. 4. By June 1964, as part of Project Dugout, specialists attempted to determine how effective the use of nuclear charges was for trenching . As part of this project, five 20-ton nitromethane charges were simultaneously detonated in hard rock . The result was a ditch with fewer debris remaining at its ends than at its sides [13] : pp. 25–26 .

Only the stimulation of gas production received sufficient industrial support to allow the transition to real field experiments. From 1967 to 1973, three joint industrial-governmental experiments were conducted in low-permeability gas fields within the framework of the American Plowshare program, aimed at intensifying gas production. Already in the early 1970s, the American public was extremely negative about any developments that contributed to the release of even minimal radioactivity. With the completion in December 1974 of tests at the Rio Blanco field, conducted with the aim of increasing gas production by explosion, the program for intensifying production and research into other possible applications was rapidly curtailed [7] : p. 5 . In 1977, the Americans stopped funding the Plowshare program [4] : p. 74 .

The Union of Soviet Socialist Republics, having joined the enthusiasm for the peaceful use of atomic energy , presented its own vision. As early as November 1949, Ambassador Andrei Vyshinsky , having taken the podium at the UN , supported the efforts of Soviet specialists developing nuclear weapons [20]: p. 2. In his speech, he spoke about the possibility of using atomic energy for national purposes [4]: p. 30 [8] . Later, Russian engineer Georgy Iosifovich Pokrovsky proposed using nuclear charges in large engineering projects such as rerouting rivers, building dams and laying canals [21] . The director of the newly created program for conducting nuclear explosions for peaceful purposes was Aleksandr Dmitrievich Zakharchenkov , who had established himself as the chief designer of the nuclear laboratory in the city of Snezhinsk ; Oleg Leonidovich Kedrovsky was nominated for the post of scientific director of the initiative [4]: p. 35 . Already at the end of 1965, together with the USSR Ministry of Oil Industry, within the framework of Program No. 7, field experiments began devoted to studying the possibility of using nuclear explosions to intensify oil production; experiments were planned on the formation of cavities in salt. Initially, a significant role in adapting military explosions for peaceful use was played by the nuclear weapons laboratory located in Arzamas-16 near Gorky . Subsequently, the laboratory in Snezhinsk became the most active participant in this activity [7] .

At a conference in the USSR in November 1965 , leading weapons researchers and designers discussed the prospects for the peaceful use of nuclear explosions. Participants showed great interest in developing special explosive devices for industrial applications and reducing the radioactivity produced by explosions [4]: pp. 37–38 . Ideas discussed also included combating asteroids and powering rockets in outer space . The crisis in the gas industry that broke out in mid-1966 opened up a new opportunity to use peaceful nuclear explosions to extinguish gushing gas wells [7] . In 1966, Soviet theoretical physicist Andrei Dmitrievich Sakharov placed great hope in the idea of the possibility of constructing artificial reservoirs by arming nuclear charges underground, then declaring himself an advocate of the use of super-powerful thermonuclear explosive devices in order to prevent earthquakes and reduce stress in the earth's crust [22] . He also advised considering the use of nuclear technology in the development of mineral deposits [4]: p. 12 .

Construction of reservoirs

The city of Kurchatov in the Semipalatinsk region of Kazakhstan, the center of the Semipalatinsk test site.

Among the first proposals for the peaceful use of nuclear explosions was the creation of reservoirs for agricultural needs in the arid regions of Siberia : Semipalatinsk , Kustanai , Tselinograd , Pavlodar and Guryev . Most of the rivers and streams in these areas flow only during periods of heavy rainfall, and the rest of the year the water in them dries up. The solution proposed for implementation involved the use of nuclear explosions to create reservoirs with a capacity of 3-5 million cubic meters [7] . The first test under the program was conducted by the USSR on January 15 , 1965 [4] [23] . A charge with a capacity of 140 kilotons detonated at a depth of 178 meters in well 1004, located on the edge of the

meters, and a large lake formed behind this crest. About 20% of the radioactive products entered the atmosphere, and within a few days the radiation level on the collapse crest rose to 20-30 R/h [7]: p. 7 .

The radioactivity resulting from this test was detected in Japan , which resulted in a complaint from the United States alleging a violation of the Three-Environment Test Ban Treaty signed in 1963 [10] . The Americans demanded an explanation, regarding the incident as an accidental release caused by the use of a powerful nuclear weapon. In response, the Soviet authorities reported that it was an underground test, the minimal release into the atmosphere of which was insufficient to affect areas outside the borders of the USSR. During a further exchange of opinions, the issue was closed [24] . On October 10 , 1965, Soviet specialists conducted a second experimental explosion. An explosive device with a yield of 1.1 kilotons was placed at a depth of 48 meters in borehole 1003, located along the dry bed of the Sary-Uzen waterway within the Semipalatinsk test site. The resulting crater was initially 107 meters in diameter and 31 meters deep. Over the next three months, under the influence of artesian water flowing from a shallow aquifer, the diameter of the crater grew to 124 meters, and its depth decreased to 20 meters. Only 3.5% of the radioactive products escaped into the atmosphere, and five days after the explosion, the radiation level on the collapse ridge reached 2-3 R/h [7]: p. 8 .

Kama-Pechora Canal

From the first excavation explosions, Soviet scientists had been toying with the idea of digging a canal that would redirect the waters of the Arctic Circle to the Volga Basin and the Caspian Sea . To assess the viability of such an idea, they used two explosions conducted in the Telkem area, again at the Semipalatinsk Test Site. The first test, called Telkem-1, took place on October 21, 1968. In saturated quartz sandstone, specialists detonated a 0.24-kiloton charge, which was placed at a depth of 31.4 meters. The second experiment, Telkem-2, took place on November 12. For it, three powerful 0.24-kiloton charges were placed at the same depth - 31.4 meters. The explosive devices were placed in a line, located 40 meters apart [4] . As a result of the test, a pit was formed that was 142 meters long, 60–70 meters wide, and 16 meters deep [7]: p. 9 .

In 1969, the State Planning Committee of the Council of Ministers of the USSR accepted a proposal to develop work related to the construction of the Kama- Pechora Canal [25] . Based on concerns about the stability of the southern part of the canal, composed mainly of saturated alluvial deposits, it was decided to conduct a nuclear experiment called "Taiga". On March 23, 1971, three 15-kiloton devices were simultaneously detonated at a depth of 128 meters [4]: p. 482 [26]: p. 120 [27] . The explosion occurred 100 km north of Krasnovishersk . As a result, a series of craters approximately 700 meters long and 340 meters wide were formed, the depth of the trench was 10-15 meters [10] . An hour later, a radiation dose of 50-200 R/h was recorded at the test site. After eight days, at a distance of 8 kilometers downwind, the radiation was only 23–25 μR/h [7] .

During the test, the USSR used a new low-fission explosive device. However, the emitted radioactivity caused concern in the United States and Sweden , who saw the test as a violation of the Treaty [7] [9] [27] . In January 1975, the results of the Taiga experiment were presented at an international meeting on nuclear explosions, and plans were announced to continue the canal

construction project [28] . However, already in the late 1970s and early 1980s, opposition to large-scale water diversion projects was evident among Soviet scientists due to environmental concerns [29] . By the mid-1980s, the canal project was abandoned [7] :p. 10 .

Construction of dams

Diamond pipe Udachnaya.

In 1974, several years after the Taiga experiment, a low-power explosion, nicknamed "Crystal," thundered near the Siberian village of Udachny on October 2 [4] : p. 278 . This test was commissioned by the USSR Ministry of Non-Ferrous Metallurgy and the Yakutalmaz diamond mining company to create a small lake for storing mining waste [7] . The explosive device, with a capacity of 1.7 kilotons, was placed at a depth of 98 meters, resulting in the formation of a dome-shaped embankment with a diameter of 180 meters and an initial height of 60 meters, which over time settled to an average height of 10 meters above the original surface [30] : p. 71 .

A study conducted in 1990 showed that under normal conditions the radiation level near the dam was 15–30 μR/h, with individual peaks reaching 110 μR/h [31] . The dam was then covered with a six-metre layer of rock from a nearby quarry, and the radiation level dropped to background levels. No radionuclides were detected in water samples from the dam area or in the adjacent soil [30] . On 7 December 1974, another excavation explosion, dubbed "Lazurit", took place at the Semipalatinsk test site. The test aimed to create a landslide dam by detonating a 1.7-kiloton charge under a 20° slope of folded quartzite and chert; the explosive device was placed 75 metres deep [26] : p. 121 . The explosion resulted in the formation of a pile of broken rock 200 meters in diameter and 14 meters high [4] : pp. 282–283 .

Intensification of oil and gas production

While planning the nuclear extraction program and the explosion of the Chagan reservoir, the USSR also studied the possibility of using nuclear explosions to intensify industrial processes, in particular for oil production. This project was implemented in cooperation with the USSR Ministry of Oil Industry [7] : p. 11. The Grachevskoye field, located 150 kilometers north of the city of Orenburg, became the first site for such an experiment. The limestone layer, located at a depth of 1000-1500 meters, had a predicted final oil yield of about 25% of the available resources [4] : p. 361 [32] .

At the initial stage of the Butane project, on March 30, 1965 , two nuclear devices with a yield of 2.3 kilotons were detonated in the Grachevskaya Formation at a depth of 1,341 meters [26] : p. 119 . Then, on June 10 , a single explosion with a yield of 7.6 kilotons thundered at a depth of 1,350

times [4]: p. 363 . Initially, the tritium content in the gas corresponded to the 0.03 µCi/l mark, but over the course of three years it decreased to 0.003 µCi/l. Traces of fission products were detected - cesium-137 and strontium-90 , but their content did not exceed 0.1 µCi/l [30]: p. 101 . Two more explosions with a capacity of 3.2 kilotons took place on June 16 and 25, 1980 at a depth of about 1,400 meters [7] [26]: p. 123 .

The second major project was called "Griffin" and covered the development of the Osinskoye field, located 100 km southwest of Perm [4]: p. 365 . On September 2 and 8 , 1969, two 7.6-kiloton charges were detonated within the area at depths of 1,212 and 1,208 meters, separated by 1,200 meters [26]: p. 120 . The camouflage explosions carried out by Soviet specialists made it possible to increase the productivity of the field by 30-60% [32] . The levels of radioactivity in the oil extracted from the field were similar to those observed by scientists at the Butan site. Nevertheless, the explosion led to the emergence of radioactivity in wells adjacent to the explosion sites - after several years, contamination was noted at 65 sites. Near the blown-up wells, the radiation dose reached 60 µR/h, and in some areas was three mR/h [7]: pp. 11–12 [34] [35] .

By the autumn of 1976, the USSR had moved on to a new stage of the programme to intensify gas production using nuclear explosions, carried out by the USSR Ministry of Geology . The objective of the Neva project was to increase gas production by conducting a series of explosions in the hydrocarbonate strata. The target deposit, Sredne-Botuobinskoye , consisted of dolomite and limestone strata covered by salt at a depth of 1,500–1,600 metres; they contained both oil and gas [7]: p. 12. The first experiment, called Oka, took place on 5 November 1976. The explosion, with a capacity of 15 kilotons, occurred at a depth of 1,522 metres [4]: pp. 368–369 [26] . Several months after the explosion, production tests were conducted at a nearby exploration well, which showed a significant increase in gas production, from 3,000–5,000 cubic meters per day before the explosion to over 100,000 cubic meters per day after the explosion. In addition, oil production was 20–22 cubic meters per day. The well continued to produce significant volumes of gas, with a flow rate of 50,000 cubic meters per day by the end of the test period [7] .

On October 8, 1978, a second explosion, called Vyatka, took place near the Oka test site. The charge was placed at a depth of 1,545 meters [26]: p. 122 . The test had flow rate characteristics similar to Oka and was conducted 120 meters from another exploratory well. For two months after the explosion, production at Vyatka averaged 60,000 cubic meters of gas per day, and after the tests had concluded, it dropped to 38,000 cubic meters per day [36] . The third explosion, Sheksna, followed a year later, on October 8, 1979 . In 1982 and 1987, three more explosions were conducted at the site: Neva-1, Neva-2, and Neva-3. The last explosion occurred in August 1987. Then Soviet specialists detonated a 3.2-kiloton charge placed in a salt formation at a depth of 815 meters [26]: p. 125 . During the tests, scientists established that the explosions not only mechanically change the surrounding rock, but also generate the phenomenon of constant electrical polarization . This polarization is directed toward the explosion site and helps direct the flow of oil to the center of the explosion. The effect discovered during the Neva project depended on the properties of the rock and was effective primarily for deposits with low permeability [7]: p. 12-13 [37] [38] .

In 1981, the Soviet Union launched Project Helium, an attempt to increase oil production in the

other and had similar yields. [30] :p. 42] Additional Soviet projects in this area included the Angara and Benzene projects, both in Western Siberia . The Angara project, carried out on December 10 , 1980, at the Yesi-Yogovskoye oil field, involved a 15-kiloton explosion at a depth of 2,485 meters [4] . The Benzene project, carried out on June 18 , 1985 , at the Sredne-Balykskoye oil field, involved a 2.5-kiloton charge that detonated at a depth of 2,860 meters [7] [26] .

Development of cavity formation technology


Landscapes of Atyrau region

In the early stages of the Soviet nuclear explosion program, considerable effort was devoted to developing a technique for creating cavities in salt formations. The site for the experiments was selected by scientists approximately 180 kilometers north of Astrakhan , in the Caspian Sea region, near the village of Azgir (now the Kurmangazy district of the Atyrau region of Kazakhstan). The area was a vast semi-desert with two large salt domes , the western and eastern, covered by a thin alluvial layer. The Halite project began on April 22, 1966, with Experiment A-1. The test was conducted on the Western Dome, where a 1.1-kiloton explosion occurred at a depth of 161 meters [4] : p. 479. The result was a cavity 25 meters in diameter and with a volume of 11,200 cubic meters. Shortly after the explosion, the cavity began to fill with water, and about 8,000 cubic meters of rock salt were poured into it. Radioactive gases escaped from the cavity through adjacent monitoring wells and eventually reached the surface [7] : p. 14 .

The next experiment, called "A-2", took place on July 1, 1968, also within the Western Dome, approximately eight kilometers north of the A-1 facility. The experiment involved a much more powerful 27-kiloton explosion at a depth of 600 meters, which resulted in the formation of a spherical cavity with a radius of about 32 meters and a volume of 150,000 cubic meters [4] : p. 480 [26] . Although this cavity also began to leak and fill with water, no gaseous radionuclide emissions were observed in the first minutes. Experiments "A-1" and "A-2" provided information on the formation of cavities in salt and their handling. The A-2 facility was primarily useful for experiments related to the production of transplutonium elements [7] .

On December 22, 1971, at a distance of 16 kilometers to the east of the previous testing grounds on the Eastern Dome, Soviet specialists conducted a third experiment - "A-3" [4] : p. 483 . During the test, an even more powerful 64-kiloton explosion was carried out at a depth of 986 meters. The resulting spheroidal cavity had a horizontal radius of 38 meters and a vertical radius of 33 meters [7] . The chamber remained dry and was subsequently used for a repeat explosion "A-3-2", which thundered in March 1976 [26] : p. 57 [39] . During the detonation of the "A-4" device on July 29, 1976 at a depth of 1,000 meters, specialists managed to produce 15 kilograms of plutonium-239. Finally, on September 30, 1977 , the A-5 explosion occurred at a depth of 1,500 meters. The resulting cavity was filled with water - this is how scientists were able to calculate the rate of reduction of the [26]

In the 1960s, Soviet scientists were faced with the problem of gas well fires and began investigating nuclear explosive devices as a solution. The first major incident occurred on December 1, 1963 , at well No. 11 of the Urtabulak gas field in southern Uzbekistan . Control of the well was lost at a depth of 2,450 meters, with daily gas losses amounting to 14 million cubic meters [4]: p. [7] [26]: p. 42 . At the time, the gas pressure in the reservoir was between 27.4 and 30.4 megapascals [40] [41] . By the fall of 1966, it was decided to use a nuclear explosion to close the well. To approach borehole #11, two inclined shafts were drilled – #1c and #2c, designed for a depth of about 1,500 meters with a clay zone thickness of 200 meters. Acoustic and electromagnetic methods made it possible to estimate the distance between borehole #11 and the hole for placing the explosive device at 35 ± 10 meters. A 30-kiloton nuclear charge created for this task was placed in borehole #1c and detonated on September 30, 1966. As a result, the gas flame went out 23 seconds after detonation, and the borehole was successfully sealed [7]: pp. 14–15 .

Several months later, another high-pressure well, No. 2-P, drilled in the Pamuk gas field, encountered similar problems. Drilling reached 2,748 meters before the gas pressure reached 58.8 megapascals. The well initially self-locked, and later began leaking gas to the surface. After unsuccessful attempts to seal it by hydraulic fracturing, a new inclined shaft, No. 10-N, was drilled, intersecting the 2-P shaft. At a depth of 2,440 meters, the minimum distance between wells was taken to be 30 ± 5 meters [7]: p. 15 . A special explosive device with a capacity of 47 kilotons was detonated on May 21, 1968 [4]: p. 374 . For seven days, due to seepage into the surrounding formations, the gas inflow continued, but eventually the well was sealed [7] .

The final instance of nuclear charges being used to extinguish fires at gushing wells occurred in 1981 at the Kumzhinskoye gas field , located in the Pechora River area, approximately 50 kilometers north of Naryan-Mar . Control over the well was lost on November 28, 1980, resulting in daily gas losses of approximately 2,600,000 cubic meters [7] . On May 25, 1981, a 37.6-kiloton Pyrite device was detonated at a depth of 1,511 meters in a sand-clay formation near the well; the explosion failed to achieve its intended goal of shutting the well [4] [30]: p. 50–51 . Studies have shown that the level of radioactivity did not exceed normal background levels at the surface [30]: p. 151 .

Cavities for underground storage of gas condensate

Following successful experiments in creating cavities in salt formations at Azgir in 1966 and 1968, Soviet scientists explored the possibility of using such cavities for industrial purposes, particularly for underground storage. In the late 1960s, negotiations began with specialists from various ministries, including the oil, gas, chemical, and oil refining industries, to determine their storage needs and interest in nuclear explosion technology for these purposes. The greatest interest was shown by the USSR Ministry of Oil Industry , which resulted in a program for the development of industrial storage facilities. The very first specialized experiment in constructing an underground storage facility was the Magistral project, conducted at the Sovkhoznoye gas field, which was located approximately 70 kilometers northeast of the city of Orenburg [7] . On June 25, 1970, a nuclear explosion with a yield of 2.3 kilotons was carried out at a depth of 702 meters in a salt layer [26]: p. 120 .

immediate vicinity [4]: p. 289 [7] . Having achieved success with the Magistral project, Soviet scientists moved on to the Sapphire project, located about 100 kilometres southwest of Magistral, near Orenburg [7]: p. 16 . This project involved two nuclear explosions in a salt formation overlying the Orenburg gas condensate field. The first explosion, carried out on October 22, 1971 , had a yield of 15 kilotons and formed a cavity with a volume of 50,000 cubic meters [4]: p. 483 . The yield of the second explosion, which thundered on September 30, 1973, was 10 kilotons [4]: p. 44 . After these explosions, a gas processing complex was built in Orenburg, and since 1974 the cavities have been used to store gas condensate . In 1993, operation of the facilities was suspended for the duration of repairs and decontamination due to increased radiation in certain areas [4] .

In 1980, at the instigation of the USSR Ministry of Gas Industry , a new project was developed, which was named "Vega". Situated on the northern edge of the Caspian Sea, approximately 700 kilometers south of the previous "Sapphire" facility, the "Vega" site was located on the recently discovered Astrakhan gas condensate field [7] . The implementation of the "Vega" project began with the first nuclear explosion on October 8, 1980. The explosion with a capacity of 8.5 kilotons thundered in a salt formation at a depth of 1,050 meters. Already the following year, on September 26, 1981, two more explosions with similar capacity were carried out at a comparable depth, separated by four minutes. On October 16 , 1982, an additional four explosions were carried out at the "Vega" site at intervals of five minutes. Among the subsequent cases of detonation of nuclear devices at Vega were six explosions on September 24, 1983 , all of which took place at a depth of about 1,000 meters [4]: p. 490–491 . On October 27, 1984, two more explosions were carried out, they were less powerful – 3.2 kilotons each [26]: p. 125 .

In 1983, the USSR began implementing the Lira project at the Karachaganak gas condensate field . The mineral deposit was discovered in 1979 and developed in the early 1980s . [7] By 1983, a decision was made to build a plant at the field to process the gas condensate . [42] [43] That same year, on July 20 , three 15-kiloton explosions were carried out at five-minute intervals as part of the Lira project. The first two explosions occurred at depths of 907 and 917 meters, and the third at a depth of 841 meters. [4]: p. 491–492 . They were followed by another series of three explosions on July 21, 1984, again with a yield of 15 kilotons and at different depths . [26]: p. 124 . Six explosions were supposed to create about 300,000 cubic meters of underground storage. Ultimately, 24 storage facilities were blown up at the Orenburg, Astrakhan and Karachaganak fields, only 13 of which served the purpose of storing gas condensate: it was decided to lock the formation gas mixture in chambers 14T and 15T; cavities 5T, 7T and 5Tk were filled with water, and others were left without fountain equipment [4]: p. 330 [44] .

Crushing of ore materials

In the early 1960s, Soviet scientists proposed using controlled explosions with a yield of 2–4 kilotons to more effectively destroy rock [45] [46] . The method involved creating vertical slits that would act as shock wave reflectors, helping to destroy the rock and minimizing the compaction of the underlying material. It was hoped that this technique would be far more effective than conventional solutions: it could potentially destroy ten times more rock than an explosion of similar size without a slit. The first practical application of this technique occurred on September

from the deposit. A special device was used to divert radioactive by-products into barren rock 120 meters from the ore body. This approach had previously been tested at the Degelen Mountains test site : experiment 148/1 in April 1971 and 148/5 in December 1974 [30] .

The site of underground nuclear explosions at the Kuelporr deposit in Khibiny.

The next experiment, called Dnepr-2, took place on August 27, 1984. This time, two 1.7-kiloton explosions were simultaneously carried out in separate adits 75 meters apart [26] : p. 125 . In total, as a result of the two Dnepr experiments, Soviet specialists managed to crush more than 1.5 million tons of apatite ore. The Dnepr-1 explosion was immediately followed by a leak of radioactivity, ultimately irradiating nearby Kirovsk with doses of 30–40 milliroentgens, about 10% of the total annual radiation background. The Dnepr-2 explosion also resulted in a leak: this time it occurred with a 10-hour delay, and the radiation outside the site was estimated to be insignificant. The safety standards established at the mine were not exceeded, and the radioactive contamination of the ore did not rise above the permissible levels [7] : p. 20. According to the results of monitoring the air and water quality in the mine and the environment in terms of radionuclides, only the concentration of tritium in the mine water in places exceeded the normal level by 1.5-2 times [30] : pp. 63-66 . The publication of information about the Dnepr experiments caused a protest from environmental organizations, which began to advocate for the cessation of nuclear testing. In 1992, it was decided to close the facility [7] .

Toxic waste disposal

In the early 1970s, the USSR Ministry of Oil Refining and Petrochemical Industry introduced a new approach to the disposal of hazardous industrial waste. The goal was to develop a method that would cope with the most complex products of production, while allowing time to develop more sophisticated waste treatment methods. As a result, two experiments were conducted using nuclear explosive devices that allowed the construction of underground toxic waste disposal facilities. A site in Bashkiria , approximately 30 kilometers west of Sterlitamak , was chosen for these experiments . The intention was to detonate nuclear devices to create underground chambers in a 400-meter-thick layer of dolomite [7] . Both experiments used 10-kiloton nuclear devices. The first test, called Kama-2, was conducted on October 26, 1973. The second, Kama-1, followed on July 8, 1974 [26] : p. 121 . Between 1976 and 1993, more than 23 million cubic meters of industrial waste, containing more than 1,000 tons of suspended particles, were placed at these sites. Between 1983 and 1993, about 700,000 cubic meters of waste from the Salavat Oil Refinery were disposed of . All explosions were completed without immediate release of radioactive products [30] : pp. 54–57 [48] .

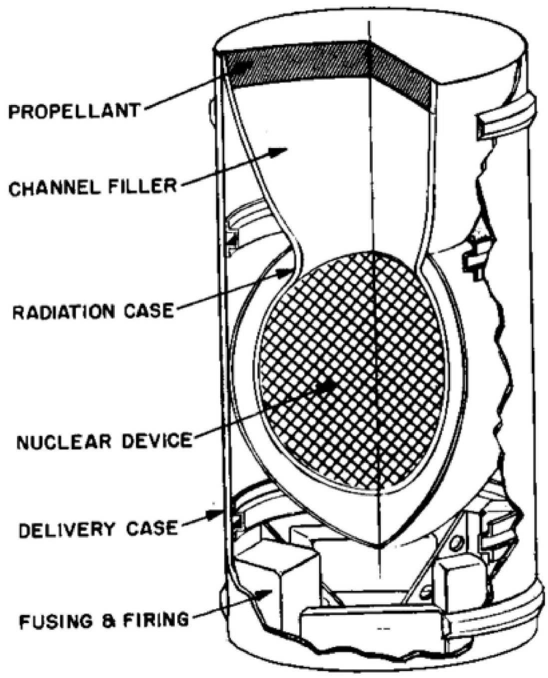
Preventing gas emissions

By the late 1970s, more than 200 explosions or rock fractures were occurring annually in the Donets Basin [7] : p. 23 . In response, experts proposed using a controlled nuclear explosion to

inclined drift located 45 meters below the Devyatka seam and 31 meters above the Kirpichevka seam [26] : p. 48 . To prevent the release of fission products, the drift was sealed with concrete; radiation levels were continuously monitored at the surface and in the mine [7] . The nuclear device exploded at a depth of 903 metres on 15 September 1979. Following the explosion, mining operations at the Devyatka seam between 1980 and 1982 showed that the explosion had reduced the risk of hazardous emissions within a radius of approximately 150 metres. The number of emissions was reduced to less than one per million square metres, and the power of each emission was reduced to less than 50 tonnes [26] . The radiation content of coal mined from the seam remained at background levels; mining operations from 1980 to 1982 proceeded without incident. Production increased significantly during these years [30] : pp. 58–60 . However, the effectiveness of the tests was questioned, in particular V. G. Revskiy, who headed the Yunkom mine, claimed that there were no significant changes for the better after the explosion [49] [50] [51] .

Legal status of peaceful nuclear explosions

The very idea of the possibility of using nuclear charges, viewed through the prism of peaceful purposes, was taken as an obstacle designed to prevent the ban on the development and testing of nuclear weapons. Permission to carry out peaceful nuclear explosions forced the consideration of measures that would prevent the accumulation of knowledge by the parties carrying out these explosions that would be useful in the development of atomic weapons, for example, because nuclear scientists from a certain country would have the opportunity to design a better weapon, having accumulated experience in improving peaceful charges, despite the design requirements for the peaceful shells being manufactured. Finally, the design of shells used in excavation would imply primarily the desire to reduce the ratio of fission and fusion yields [4] [20] : pp. 61-62 . Such an endeavor could only be provided with ideas by scientists from the country that was developing the nuclear device and conducting an analysis of the microscopic particles emitted by the explosion caused by this device [20] .



The Orion apparatus was designed to provide pulsed thrust using such a cumulative charge.

Following the Soviet Union's detonation of its first thermonuclear device on August 12, 1953 , U.S. President Dwight David Eisenhower set out to overcome the political challenges posed by the nuclear arms race . [52] [53] In a speech to the United Nations on December 8, 1953, Eisenhower called for the peaceful use of atomic energy, introducing the concept of "Atoms for Peace." Rather than working to reduce military arsenals, he recommended turning nuclear technology to peaceful uses, believing that with sufficient resources, engineers could repurpose atomic potential for large-scale and useful applications in the interests of humanity . [54] In early 1954, the United States approached the United Nations, calling for it to sponsor a Conference on the Peaceful Uses of

At the Nuclear Test Ban Conference held in Geneva in 1958 , American Ambassador James Wordsworth indicated the interest of the United States in ensuring the possibility of conducting peaceful nuclear explosions in defiance of the nuclear test prevention regime. The position of the American delegation consisted of a proposal to organize an international stockpile of nuclear explosive devices, provided by each country that expected to organize explosions for peaceful purposes [56] . Wordsworth's control regime assumed permission to use peaceful nuclear charges that meet defined requirements and undergo verification by the Control Commission. The Soviet delegation did not take this proposal into account [20] : p. 61. On December 15, 1958, the United States invited the Control Commission, which was being formed, to begin establishing procedures that would be able to ensure control of nuclear devices and observation of explosions carried out for peaceful purposes [57] . The response to this invitation was the displeasure of the negotiator sent by the Soviet Union, Semyon Tsarapkin , who reminded the Americans of the main task of the Conference - the development of an unconditionally enforceable agreement banning nuclear weapons tests [58] .

The Soviet state changed its strictly oppositional rhetoric on December 25, 1958, with a speech at a meeting of the Supreme Soviet of the USSR by Andrei Gromyko , who allowed peaceful nuclear explosions to be carried out, provided that in this case Western and Eastern countries undertake to carry out an equal number of tests, during which only devices approved after a full internal and external review are allowed to be used [59] . A similar proposal had already been voiced by the American Edward Teller at the March hearings in Congress , when he advocated for an international inspection of the devices, carried out by studying both the explosion itself and the internal structure of the charge, but at the same time noted that the layer of information obtained in this way could contain classified information [60] .

On January 30, 1959, Ambassador Wordsworth presented preliminary procedures for peaceful nuclear explosions for discussion. The draft article proposed by the United States called for notification four months before the use of an explosive device about the technical details of the explosion and, in particular, about the measures that would be taken by the implementing country to prevent radioactive fallout beyond the designated vicinity [61] . The American proposal also declared the feasibility of verification by the providing party of any charge transferred under its responsibility, which would be monitored by representatives of the other countries participating in the agreement. The United States saw an alternative procedure in which each of the parties would have the opportunity to use new nuclear devices without being tied to time, but only on the condition that the other parties would be able to study the design of the charges, including becoming familiar with the detailed drawings of these charges [20] : p. 63 .

On February 23, 1959, the US proposals were met with a response from Ambassador Tsarapkin, who criticized his American colleague's desire to turn the conference into an attempt to legalize nuclear testing [62] . Nevertheless, the Soviet delegate expressed his readiness to agree to include peaceful explosions in the treaty banning nuclear experiments, given that the treaty would then force American and British scientists to match the USSR in the number of explosions they carried out. In exchange for the American plan to organize a certain stock of nuclear devices intended for the implementation of peaceful explosions, Tsarapkin called for the advance transfer to the other side of a comprehensive description of the charge and its drawings, and also proposed allowing an outside observer to become familiar with the internal and external structure of the projectile being used [63] . The Americans accepted the Soviet project for consideration, informing the UN of the agreements reached, which allowed peaceful nuclear explosions monitored by international representatives under agreed conditions [64] . On March 21, 1961, the United States officially

In July 1963, Moscow provided a platform for negotiations during which the Three-Environment Nuclear Test Ban Treaty was agreed upon [66] . The agreement prohibited any nuclear explosions that would be capable of causing radioactive fallout beyond the borders of the state initiating such explosions [67] . American negotiators insisted on softening the terms of the signed treaty, which would consist of allowing peaceful nuclear explosions upon reaching a unanimous agreement with the parties involved [68] . Such explosions also had to comply with the requirements of a certain appendix, which the Americans did not submit. The Soviet delegation refused to add a corresponding provision to the treaty [20] : p. 65. Over the course of a decade, the treaty was ratified by more than 80 states, and over 110 states decided to sign it [52] .

The Treaty on the Non-Proliferation of Nuclear Weapons, approved in June 1968, prohibited non-nuclear powers from acquiring nuclear weapons; this restriction came into effect in 1970 [66] . At the same time, the agreement required nuclear states not to transfer to non-nuclear countries either finished weapons, or material for them, or technology that would allow them to be manufactured independently, but to ensure access to the peaceful use of nuclear energy; the International Atomic Energy Agency acted as a guarantor of the latter requirement [69] . Subsequently, the Agency's responsibilities also included coordinating the interests of the international community affecting peaceful nuclear explosions: these interests were reflected in Article V, which supplemented the treaty, obliging states with nuclear weapons to provide access to the possible benefits arising from the implementation of nuclear explosions for peaceful purposes [53] . Within seven years, the treaty, which was opened for signature on July 1, 1968, was signed by 106 states, and another 83 governments ratified it [52] .

In the spring of 1969, the USSR proposed a series of bilateral negotiations with the United States that would concern peaceful nuclear explosions. The series began with negotiations in Vienna , which took place on April 14–16 , 1969 [20] : p. 10 . On February 12–17 , 1970, Soviet delegates met with the Americans in Moscow, and on July 12–23 , 1971, they met with their colleagues in Washington . The final meeting took place in Vienna, on January 15–17 , 1975. These meetings allowed Soviet scientists to reveal a number of technical details of their early experiments and to talk about several applications they were developing [7] : p. 6 . The USSR also reported on the scale and technical results of its program at meetings of the Group on Peaceful Nuclear Explosions at the International Atomic Energy Agency in Austria , organized in Vienna in the early 1970s [28] [53] .

In 1973, negotiations took place on the Treaty on the Limitation of Underground Nuclear Weapons Tests. While the Americans proceeded only from the fact that any established limitation on the power of nuclear charges should be unconditionally applied to peaceful explosions, regardless of whether such explosions were carried out at a test site or outside it, the First Deputy Chairman of the State Committee for the Use of Atomic Energy of the USSR Igor Morozov , who represented the interests of the Soviet state, advocated that the power of peaceful explosions outside special test sites be set as high as possible, up to 600 kilotons: charges of such power would make it possible to build, for example, the Kama-Pechora Canal [20] : p. 67. In the end, the negotiators approved a limit of 150 kilotons - it was supposed to be used in relation to all nuclear weapons tests carried out at designated test sites [70] . In July 1974, the parties signed an agreement declaring the adopted restrictions in force from March 31 , 1976, the Treaty on the Limitation of Underground Nuclear Weapons Tests [66] .

By the time the Treaty on Underground Nuclear Explosions for Peaceful Purposes was signed in May 1976, the Soviet Union had abandoned the idea of blowing up the Kama-Pechora Canal, and

peaceful nuclear explosion with a yield of over 35 kilotons now required third-party inspection, and a powerful explosion of over 50 kilotons required hydrodynamic measurements. The treaties themselves were amended and ratified in the fall of 1990 [20] [70] [71] .

From the statement made on November 2, 1977 by the General Secretary of the Central Committee of the CPSU Leonid Brezhnev , it followed that the Soviet state intended to adopt a moratorium that would prohibit the implementation of peaceful nuclear explosions until the Comprehensive Nuclear-Test-Ban Treaty ceased to be in effect [20] : p. 69. The Chairman of the Presidium of the Supreme Soviet of the USSR then proposed to stop the production of nuclear weapons by countries and called for the beginning of the disposal of the shells accumulated over time in order to eventually achieve their complete destruction [72] . Following Brezhnev's statement, a new head of the Soviet delegation, Andranik Petrosyants , already the well-known boss of Morokhov and the chairman of the State Committee for the Use of Atomic Energy of the USSR, was appointed. On October 19, 1989, the USSR adopted a moratorium that did not allow nuclear tests for another year. Just as it was during the moratorium of 1985-1986 , scientists did not conduct a single peaceful nuclear explosion. The Soviet state no longer initiated nuclear explosions for peaceful purposes after the last such explosion thundered on September 9, 1988. The Soviet Union conducted its final nuclear test in October 1990 [20] .

The Soviet moratorium was extended several times, the US Congressional restrictions on nuclear testing were agreed upon, and the French moratorium was accepted before talks were held in January 1994 to focus on the Comprehensive Nuclear-Test-Ban Treaty. US and British negotiators now advocated a ban on all nuclear explosions. France, which had previously considered peaceful nuclear explosions in the late 1970s, defended similar interests. Russia also advocated a ban on peaceful explosions, and only China , despite its previous disinterest in the peaceful use of nuclear explosive devices, expressed a desire to allow such use [20] . Throughout 1994–1995, the nuclear-armed states maintained these positions until, on June 6, 1996, Chinese negotiators made a concession in the form of a proposal to consider the issue of peaceful explosions at a separate conference, which the delegates agreed to finalize within 10 years. Eventually, all countries except India , Pakistan, and North Korea reached an agreement, which was reflected in the Treaty, which was signed by each of the five nuclear powers on September 24, 1996 [73] . On November 2 , 2023, Russia withdrew its ratification of the Treaty [74] .

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Authors: ETUFID , Gunslinger , Lokomotiv , Alexander Nechay , Elvira Gainetdinova